

# Modeling the Pulse Profiles of Millisecond Pulsars in the Second LAT Catalog of $\gamma$ -ray Pulsars

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**Abstract.** Significant  $\gamma$ -ray pulsations have been detected from  $\sim 40$  millisecond pulsars (MSPs) using 3 years of sky-survey data from the *Fermi* LAT and radio timing solutions from across the globe. We have fit the radio and  $\gamma$ -ray pulse profiles of these MSPs using geometric versions of slot gap and outer gap  $\gamma$ -ray emission models and radio cone and core models. For MSPs with radio and  $\gamma$ -ray peaks aligned in phase we also explore low-altitude slot gap  $\gamma$ -ray models and caustic radio models. The best-fit parameters provide constraints on the viewing geometries and emission sites. While the exact pulsar magnetospheric geometry is unknown, we can use the increased number of known  $\gamma$ -ray MSPs to look for significant trends in the population which average over these uncertainties.

**Keywords:** gamma rays: observations, pulsars: millisecond

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## 1. INTRODUCTION

Millisecond pulsars (MSPs) are thought to be old pulsars which have reached very short spin periods via accretion from a companion [1]. Non-recycled pulsars have been known to emit  $\gamma$ -rays for some time but no significant high-energy (HE,  $\geq 0.1$  GeV) pulsations had been seen from any MSP prior to the launch of the *Fermi* Gamma-ray Space Telescope in 2008. Using observations with the Large Area Telescope (LAT, the main instrument aboard *Fermi*, [2]) MSPs have been established as a significant class of HE emitters via the detection of pulsed  $\gamma$ -rays, at the radio period, from  $\sim 40$  MSPs<sup>1</sup> [3].

The geometry and location of emission in the pulsar magnetosphere remain important and open questions in  $\gamma$ -ray pulsar physics. Thus, we have generated geometric simula-

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<sup>1</sup> For a list of publicly announced detections see:

<https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars>

tions and developed a likelihood fitting procedure to constrain the viewing geometries and properties of the emission regions of LAT-detected MSPs. By fitting a large sample of MSPs we can marginalize over discrepancies in the field geometry and still make meaningful statements about the population of  $\gamma$ -ray MSPs as a whole.

## 2. LIGHT CURVE SIMULATIONS AND FITTING

We assume a vacuum retarded-dipole magnetic field geometry [4] when simulating pulsar light curves, but note that this geometry is only an approximation as charges will be pulled from the stellar surface and populate the magnetosphere [5]. Simulated light curves are generated as described in [6, 7] using geometric outer gap (OG), slot gap/two-pole caustic (TPC), pair-starved polar cap (PSPC), and low-altitude slot gap (laSG) models with either a single-altitude, hollow-cone and/or core beam; altitude-limited (alTPC/OG), or laSG radio models.

We use a resolution of  $1^\circ$  in magnetic inclination ( $\alpha$ ) and viewing angle ( $\zeta$ ), both with respect to the pulsar spin axis, and of 2.5% of the polar cap opening angle in emission gap width. For the alTPC/OG models we use steps of 0.05 light-cylinder radii ( $R_{LC}$ ) in emission altitude. The laSG models have a resolution of 0.2 stellar radii ( $R_{NS}$ ) in the fading radius and 0.1 (0.3)  $R_{NS}$  in the inner (outer) fading parameter (see [7] for definitions). Accelerating particles are never followed beyond a spherical radius of 1.2  $R_{LC}$  or a cylindrical radius of 0.95  $R_{LC}$ .

We fit the simulated  $\gamma$ -ray light curves to the data using Poisson likelihood and the radio using a  $\chi^2$  statistic and then combine the two. We scan over the parameter phase space and estimate uncertainties from either 1- or 2-D likelihood profiles.

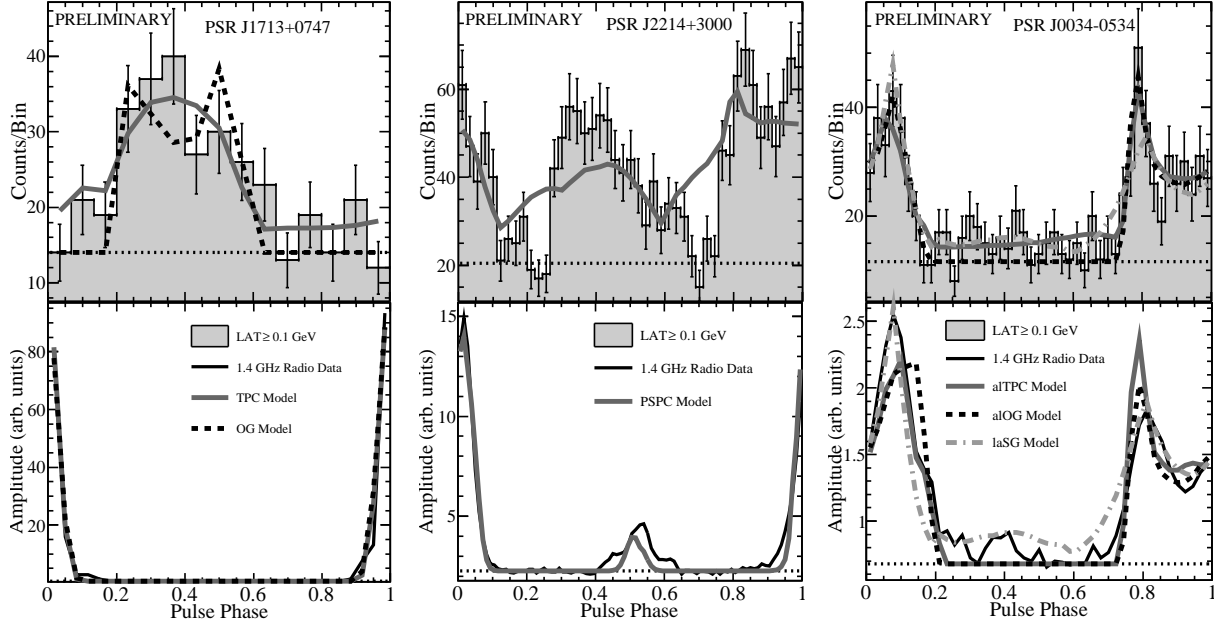
## 3. RESULTS

We have begun fitting the light curves of MSPs in the second LAT catalog of  $\gamma$ -ray pulsars (2PC, see [3] and Ö. Çelik et al., *these proceedings*). We select events from the 2PC data set within  $2^\circ$  of each MSP and having reconstructed energies  $\geq 0.1$  GeV. The best-fit spectral models are used to estimate the background levels taking into account other sources in the region.

Fig. 1 shows fits for three  $\gamma$ -ray MSPs, all of which demonstrate the importance of using not just the radio profile but also the polarization information.

The left panel in Fig. 1 shows the observed and best-fit light curves of PSR J1713+0747 using the TPC and OG  $\gamma$ -ray models with a hollow-cone plus core radio beam. Polarimetric observations detect sense-changing circular polarization through the main pulse of this MSP [8] which suggests a core component. Neglecting the core component in the modeling can lead to differences in  $\alpha$  and  $\zeta$  of as much as  $30^\circ$ .

The center panel in Fig. 1 shows the same for PSR J2214+3000 in which the  $\gamma$ -rays are fit with a PSPC model and the radio with a hollow-cone beam. This MSP had been fit with alTPC/OG models previously [9]; however, recent observations detect significant linear polarization (not expected for caustic emission [7]) and with more statistics the  $\gamma$ -ray peaks clearly lead those in the radio, all arguing against the alTPC/OG models.



**FIGURE 1.** Three example light curve fits. The top panels show the observed and best-fit  $\gamma$ -ray light curves. The bottom panels show the observed and best-fit radio light curves. Estimated background levels are indicated by dashed, horizontal lines. The model light curves are indicated in the legend for each MSP.

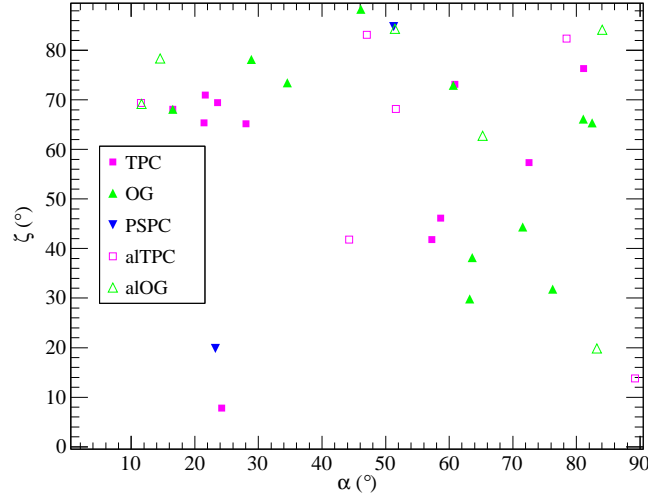
The right panel in Fig. 1 shows the same for PSR J0034–0534, an MSP with  $\gamma$ -ray and radio peaks aligned in phase. Observations of this MSP are consistent with 0% linear polarization [8] which argue for caustic radio models (i.e., alTPC/OG). Note that the polarization properties of the laSG model have not been investigated.

A similar study of MSP light curves has been performed using two years of LAT data and only 19 MSPs [9]. The best-fit  $\alpha$  and  $\zeta$  values from this analysis are shown in Fig. 2.

While the  $\zeta$  values are consistent with a random distribution of spin-axes with respect to our line of sight (preference for values closer to  $90^\circ$  where there is more solid angle) the best-fit  $\alpha$  values seem to favor all angles equally. This is in conflict with studies which suggest that the spin and magnetic axes should align as a pulsar spins down [10] or during the recycling process [11] and may indicate that the magnetic axis in MSPs (which have weaker magnetic fields) moves towards anti-alignment while spinning down, after the recycling process has completed.

## 4. FUTURE

Once we have fit the profiles of all MSPs in the 2PC we will look for population trends in viewing geometry, energetics, and best-fit model with a larger sample than what has been done previously [9]. We will also generate similar simulations using different magnetospheric geometries, explore radio cone/core models at altitudes different than those in [12], and investigate mixtures of caustic and non-caustic radio emission.



**FIGURE 2.** Best-fit  $(\alpha, \zeta)$  pairs for each MSP in [9], corresponding emission models are indicated by the legend. Note that there are two entries for those MSPs fit with TPC and OG variants.

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